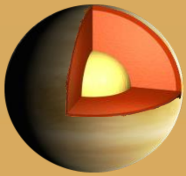
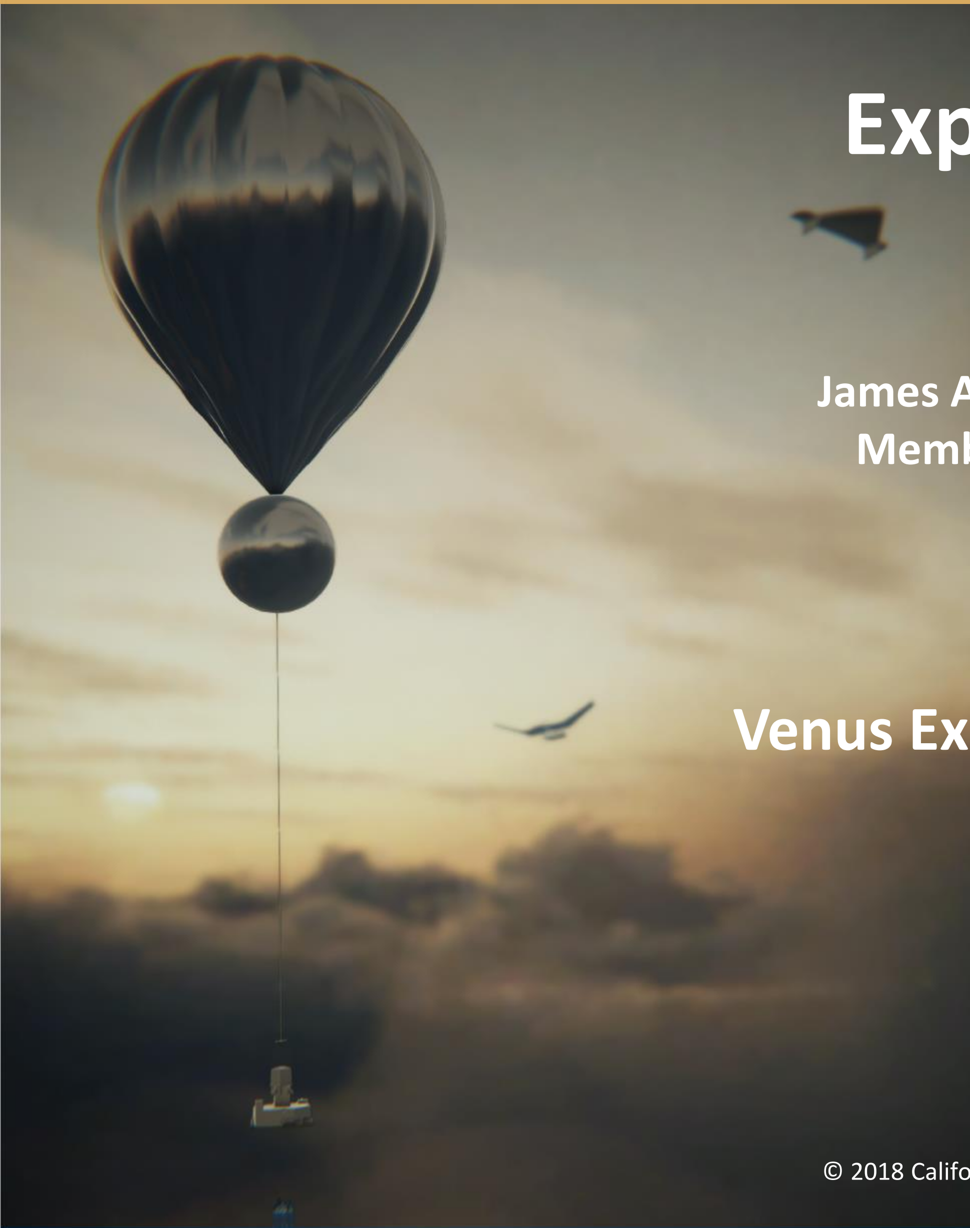




Exploration of Venus with Aerial Platforms

James A. Cutts[1], Robert Grimm[2], Jeffery L. Hall[1] , and
Members of the Venus Aerial Platform Study Team

Presentation to

Venus Exploration Analysis Group (VEXAG)

Nov 6-8, 2018

1. Jet Propulsion Laboratory, California Institute of Technology
2. Southwest Research Institute, Boulder, Colorado

Topics

- Motivation
- Venus Aerial Platforms Study Overview
- Study Participants
- Historical Context –VeGa 1 and 2 balloons
- Aerial Platforms Capability Assessment
- Aerial Platform Science Assessment
- Venus Aerial Platforms – Design Sweet Spot
- Key Findings
- Summary

Motivation

- In situ exploration of Venus has been seriously hampered by the severe environment (T =460C and P=90 bars) of the Venus surface.

- Contemporary concepts for lander missions to Venus have more sophisticated instruments but do not survive on the surface of Venus for very much longer than Soviet- era Venera landers

- There are two plausible pathways to long-duration Venus *in-situ* missions
  - Aerial Platforms operating in the temperate regions of the upper atmosphere
  - Surface Platforms utilizing high temperature electronics

- NASA’s Planetary Science Division (PSD) is currently studying both pathways for Venus exploration and is considering both concepts as U.S. provided contributions to a joint mission with Russia (Venera D)

Venus Aerial Platforms Study Overview

- NASA PSD formed a study team in April 2017 to assess the state of science and technology for aerial platforms and develop a technology plan
- Two face-to-face study meetings were held in June and December 2017 covering the science implementation concept and technical maturity
  - Scientific objectives and aerial platform options space (June 2017)
  - Technical feasibility and technology roadmap (Dec 2017)
- Following the second meeting the study team has been working on a reports with the key findings
  - A narrative summary report containing the principal findings which is about to be released and a draft has been made available to PESTO
  - A powerpoint presentation providing more details in each of the technical areas
- A more detailed narrative report is planned for early next year but will require additional resources

Aerial Platform Study Participants

- Michael Amato, GSFC, michael.amato@nasa.gov
- Giada Arney, NASA Goddard, giada.arney@gmail.com
- Dave Atkinson, JPL, David.H.Atkinson@jpl.nasa.gov
- Josette Bellan, JPL, Josette.Bellan@jpl.nasa.gov
- Kevin Baines, JPL/U. Wisc.-Madison, blueskies4321@yahoo.com
- Kumar Bugga, JPL, Ratnakumar.V.Bugga@jpl.nasa.gov
- Neil Cheatwood, NASA LaRC, f.m.cheatwood@nasa.gov
- Jim Corliss, NASA LaRC, james.m.corliss@nasa.gov
- Dave Crisp, JPL, David.Crisp@jpl.nasa.gov
- James Cutts, JPL, james.a.cutts@jpl.nasa.gov
- Maxim de Jong, Thin Red Line, maxim@thin-red-line.com
- Mona Delitsky, CSE, cal_specialty@yahoo.com
- Debbie Fairbrother, NASA Langley, debora.a.fairbrother@nasa.gov
- Lori Glaze, GSFC, lori.s.glaze@nasa.gov
- Ben Goldman, Global Aerospace.com, benjamin.d.goldman@gaerospace.com
- Jonathan Grandidier, JPL, Jonathan.Grandidier@jpl.nasa.gov
- Bob Grimm, SwRI, grimm@boulder.swri.edu
- Jeffery Hall, JPL, jlhall@jpl.nasa.gov
- Matt Heun, Global Aerospace Corp., matthew.k.heun.1@gaerospace.com
- Jacob Izraelevitz, JPL, jacob.izraelevitz@jpl.nasa.gov
- Kandis-Lea Jessup, SwRI, jessup@boulder.swri.edu
- Attila Komjathy, JPL, komjathy@jpl.nasa.gov
- Tibor Kremic, NASA Glenn, tibor.kremic@nasa.gov
- Siddharth Krishnamoorthy, JPL, siddharth.krishnamoorthy@jpl.nasa.gov
- Tim Lachenmeier, Near Space Corp., Tim.Lachenmeier@nsc.aero
- Damon Landau, JPL, Damon.Landau@jpl.nasa.gov
- Geoffrey A. Landis, NASA Glenn Res. Center, geoffrey.landis@nasa.gov
- Sebastien Lebonnois, LMD/CNRS, sebastien.lebonnois@lmd.jussion.fr
- Sanjay Limaye, U. Wisconsin, SanjayL@ssec.wisc.edu
- **Larry Matthies, JPL, lhm@jpl.nasa.gov**
- Kevin McGouldrick, U. Colorado-Boulder, kevin.mcgoudrick@lasp.colorado.edu
- David Mimoun, ISAE, France, david.mimoun@isae.fr
- Peter Ngo, Global Aerospace Corp., peter.ngo@gaerospace.com
- Kerry Nock, Global Aerospace Corp., kerry.t.nock@gaerospace.com
- Julian Nott, Consultant, nott@nott.com
- Mike Pauken, JPL, mpauken@jpl.nasa.gov
- Mina Rais-Zadeh, JPL, Mina.Rais-Zadeh@jpl.nasa.gov
- Tom Randolph, JPL, Thomas.M.Randolph@jpl.nasa.gov
- Kim Reh, JPL, Kim.R.Reh@jpl.nasa.gov
- Gerald Schubert, UCLA, schubert@ucla.edu
- Dave Senske, JPL, david.senske@jpl.nasa.gov
- Daniel Sokol, Northrop Grumman, daniel.sokol@northropgrumman.com
- Tom Spilker, Consultant, planetaryflightarchitect@yahoo.com
- Paul Steffes, Georgia Tech, stefffes@gatech.edu
- **Tommy Thompson, JPL, twthompson@jpl.nasa.gov**
- Allan Treiman, LPI, Houston, TX, treiman@lpi.usra.edu
- Eugene Ustinov, JPL, eugene.a.ustinov@jpl.nasa.gov
- Raj Venkatapathy, NASA, Ames, ethiraj.venkatapathy-1@nasa.go
- William Warner, JPL, william.n.warner@jpl.nasa.gov
- Steve Warwick, Northrop Grumman, steven.warwick@ngc.com
- Paul Wercinski, NASA Ames, paul.wercinski@nasa.gov
- Leyland Young, NASA/WFF/GSFC, leyland.g.young@nasa.gov

James Cutts, Larry Matthies and Tommy Thompson are study co-leads

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Historical Context – VeGa 1 and 2 Superpressure Balloons

- Sent to Venus by the Soviet Union in 1985:
  - 3.5 m diameter, 15 kg mass
    - Teflon-like coated fabric balloon material
    - Buoyancy provided by helium gas
  - 7 kg payload module (gondola) carried under the balloon
    - Temperature, pressure, illumination, aerosol and wind measurements (from radio tracking)

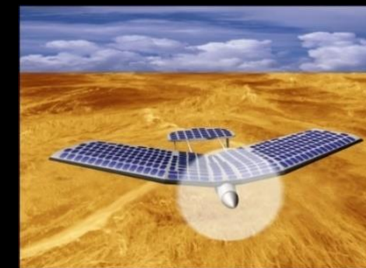
- Highly successful mission. Each balloon
  - Flew at 51-55 km altitude (in the clouds)
  - Experienced ambient temperature 30-60 °C
  - Powered by primary batteries for ~ 46 hours
  - Traveled 11,000 km around the planet
  - Entered on the night side and crossed onto the dayside

- No other Venus aerial mission has been attempted
  - Proposals for more capable balloons have been made to NASA and ESA competitive programs
  - Aerial platform concepts have been included in strategic mission concepts (**Venus Climate Mission and Venera D)**

Aerial Platform Concepts Considered

Mechanical Compression Balloon
(Thin Red Line Aerospace)

Pumped Helium Balloon
(Paul Voss CMET)

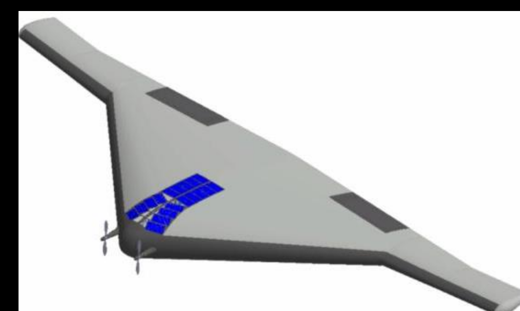


Solar Aircraft
Geoff Landis (NASA-GRC)

Superpressure Balloon (JPL Venus prototype)

Air Ballast Balloon (Google Loon)

Phase Change Fluid Balloon (JPL)



Hybrid Airship (Northrup Venus Atmospheric Maneuverable Platform (VAMP)
Northrop Grumman

Fixed Altitude

Variable Altitude

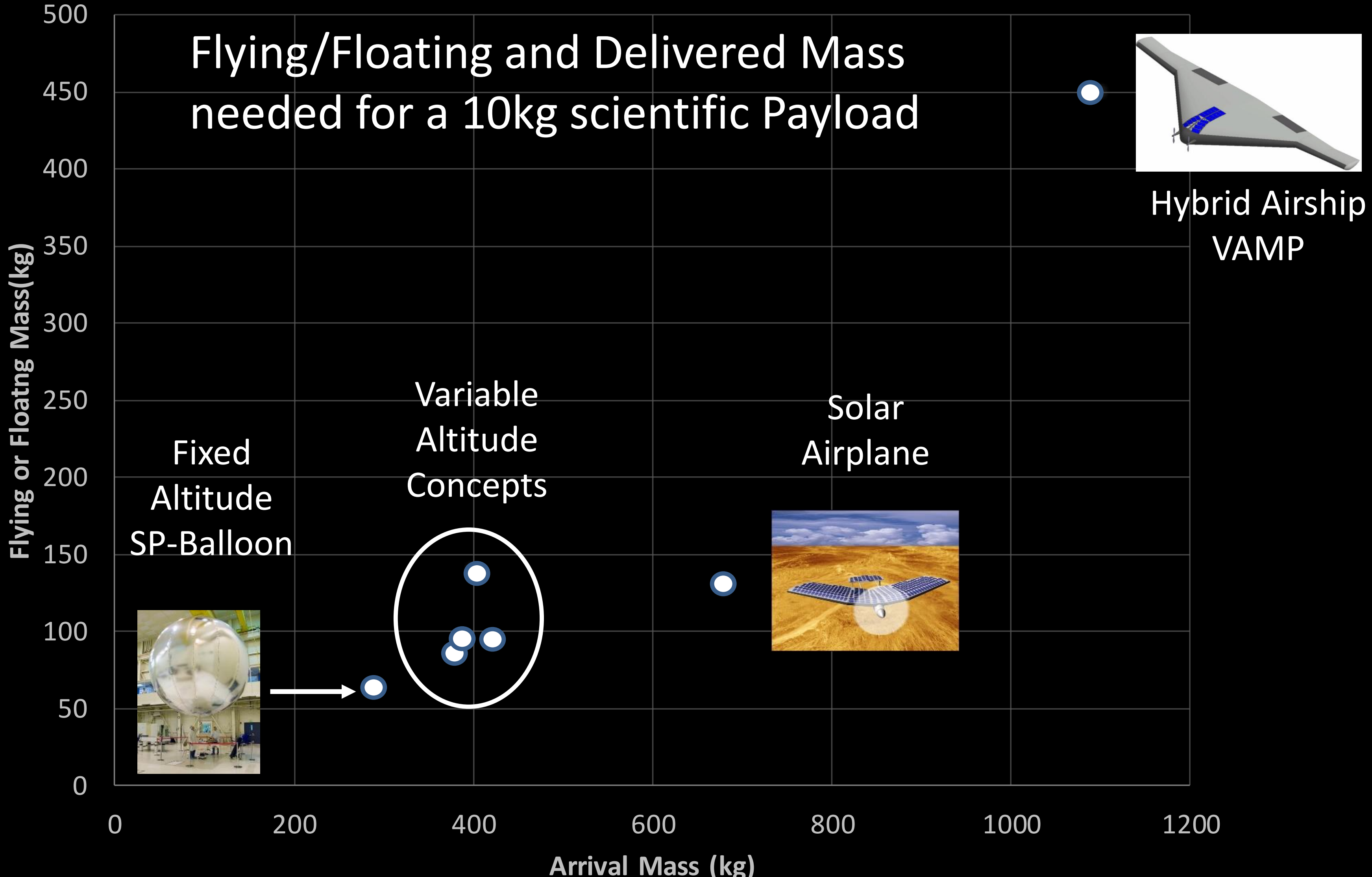
Variable Altitude and Lateral Control

Comparison of Aerial Platform Candidates

Platform Type	Main Buoyancy Method	Envelope Type	Altitude Change Method
Super-pressure Balloon	He or H_2	super-pressure	None
Pumped Helium (He)	He or H_2	zero-pressure	compress and store buoyancy gas
Mechanical compression balloon	He or H_2	super-pressure	compress envelope
Air ballast balloon	He or H_2	Zero- or super-pressure	compress and store ambient air
Phase change fluid (PCF) balloon	He augmented with a PCF (e.g., H_2O or NH_3)	zero-pressure	change of phase of PCF (e.g., H_2O or NH_3)
Solar airplane	propulsive-driven aerodynamic lift	N/A	lift modulation
VAMP	He or H_2 buoyancy augmented with aerodynamic lift	super-pressure	lift modulation

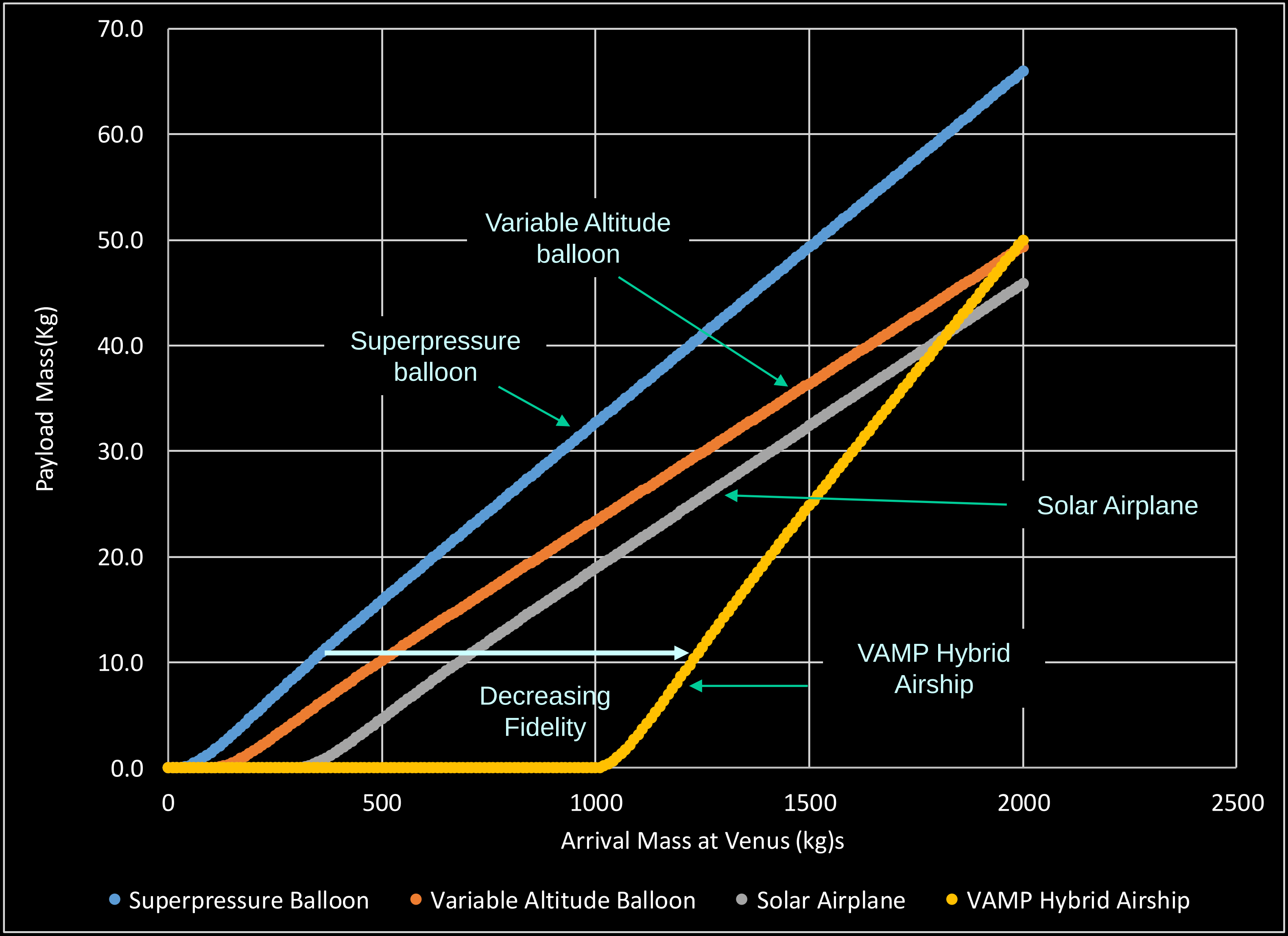
All seven concepts can be used to deploy and relay data from dropsondes or descent probes which can descend deeper into the atmosphere than the aerial platform. Details in back up charts

Venus Aerial Platform Trade Study



Comparative Analysis of Platforms

Payload Mass Projections – Scaleability



Fixed Altitude Balloon Assessment

- Most mature concept because of the VEGA experience and the 5.5m prototype developed at JPL
  - Designed to tolerate Venus day night transtion and sulfuric acid environment
  - Capable of carrying a suspended mass of 45kg.
- Deployment and inflation tests of this system also conducted
- Like VeGa this vehicle would travel consistently west on Venus at about 65 m/sec.
- Small latitude changes each pass around Venus are expected as a result of the small and variable meridional wind component

Variable Altitude Balloon Assessment

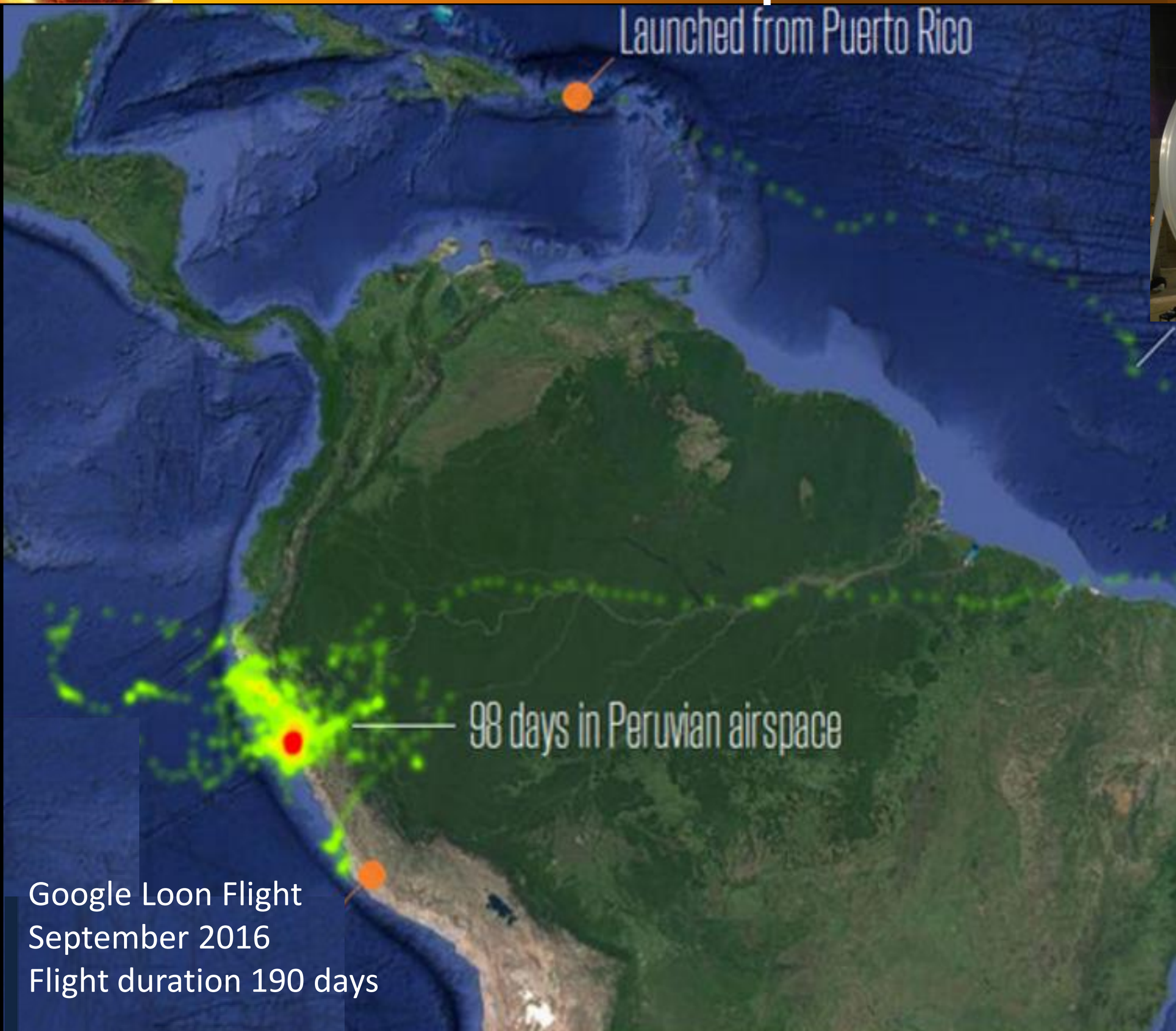
- All four variable-altitude balloons concepts are of comparable overall system arrival mass about 1/3 more than the superpressure balloon.
  - **Air Ballast balloons have a strong terrestrial heritages (Google Loon)** but on Venus pumps and balloon interior surfaces would need to be protected against corrosive gas
  - **Pumped Helium balloons** do not ingest external air but have not yet been built at the scale we need for Venus. They can be tested in terrestrial environments
  - **Mechanical compression** balloons are capable of changing altitude more quickly and with greater energy efficiency than pumped helium or air ballast balloons. They can also be tested in terrestrial environments
  - **Phase change balloons** are extremely energy efficient since they can change altitude passively and use zero pressure balloon materials that are less challenging in the harsh Venus atmosphere. However, their controls are complex and they cannot be tested in the terrestrial atmosphere

- All four concepts were evaluated for operation over an altitude range of 50 to 60 km. All four are believed to be feasible for operation down to 40 km. The phase change balloon would be more suitable for deeper dives.

- Despite no lateral control can exploit altitude and diurnal variations in meridional wind velocity to change latitude.

- All concepts appear feasible but require further analysis and prototype development to determine the best option for Venus

Altitude Controlled Balloons
Current Capabilities at Earth



Variable altitude air ballast balloon

Google Loon Flight
September 2016
Flight duration 190 days

Solar Airplane, Helicopter and Glider Assessment

- Solar airplane requires ~70% more mass than a variable altitude balloon for the 10 kg science instrument case.
  - Restriction to sustained all-daytime, near sub-solar flight above 66 km to get sufficient sunlight. Battery capabilities insufficient to support nighttime propulsion
  - Temporary excursions below 66 km are possible with duration and minimum altitude dependent on energy storage capability.

- Solar powered helicopter was ruled out early because:
  - Insufficient thrust to station keep near the subsolar point
  - Less efficient than solar airplane – less than one hour without recharging
  - Unable to land to recharge (compare Mars Helicopter)

- Glider concepts are now being explored through a NASA SBIR at JPL
  - Would exploit attributes of Venus atmosphere such as night time convection and high wind shear
  - May be of interest for a short duration experiment but unlikely to provide a reliable source of lift for a 100 day mission

Hybrid Airship - Assessment

- This concepts requires by far the most arrival mass at Venus, more than double any of the balloon options.
  - Driven by both the size of the basic vehicle and the need to carry a propulsion system to get into a large elliptical orbit.
  - Assumes aerobraking to transition to a low, near circular orbit such that the maximum entry speed becomes ≤ 8 km/s
- Has a relatively large mass before the first kilogram of science instruments gets added. However, the overall vehicle mass subsequently grows at a much reduced rate as the science payload mass is increased
- Control system is not powerful enough to station keep in the strong meridional winds but provides more predictable latitude control than variable altitude balloons
- Greatest challenge is the entry system approach which has very low technology maturity and would require a protracted development program

Aerial Platforms Technology Maturity Assessment (1 of 2)

Platform Concepts

- Fixed Altitude –SP Balloon
- Variable Altitude
  - Air ballast
  - Pumped Helium
  - Mech. Compression
  - Phase Change
- Variable Altitude and Lateral Control
  - Solar Airplane
  - Hybrid Airship

Altitude Range Studied

Nominal Range
- Design Altitude(53km, 30C)
- Excursions of (2km, 15C)

Nominal Range
- Upper limit (60km, -35C)
- Lower limit (50 km, 65C)

Extended Altitude Range (Note 1)
- Upper limit (60km, -35C)
- Lower limit (40km, 115C)

Nominal Range (Note 2)
- Upper limit (66km, -45C)
- Lower limit (62 km, -35C)

Nominal Range
- Upper limit (60km, -35C)
- Lower limit (50 km, 65C)

Note 1 : For brief excursions into the high temperature region, temperature sensitive components(electronics, sensors, batteries can be maintained below 30C)

Note 2 : Solar airplane can only fly on the day side of Venus above the clouds

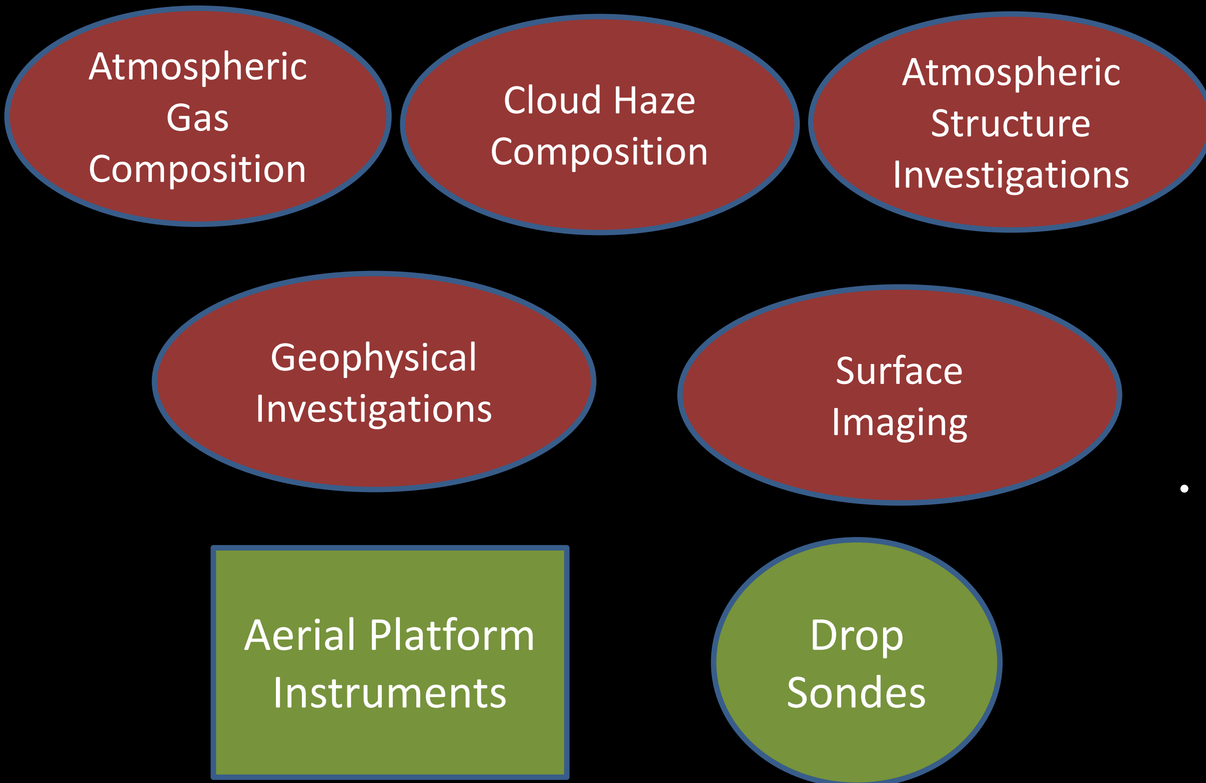
Aerial Platforms Technology Maturity Assessment (2 of 2)

Platform Type	Concept	Altitude Range	Temperature Range	Technology Maturity			
				Entry	Descent Deployment	Aerial Mobility	System
Fixed Altitude	Superpressure balloon	53 +/-2Km	30 +/-8C	Very High	High	High	High
Variable Altitude	All four concepts	50 to 60 km	-30C to 60C	Very High	High	Moderate	Moderate
Variable Altitude	All four concepts	40 to 60 km	-30C to 115C	Very High	High	Low to Moderate	Low to Moderate
Full 3D Control	Solar Airplane	60 to 67 km	-30C to -45C	Very High	High	Moderate	Moderate
Full 3D control	Hybrid Airship (VAMP)	50 to 60 km	-30C to 60C	Low	Moderate	Moderate	Low

Low | Low to Moderate | Moderate | High | Very High

Pre-Decisional Information -- For Planning and Discussion Purposes Only

Scientific Assessment of Aerial Platforms



- **Atmospheric Science**
  - **Kevin Baines, JPL/University of Wisconsin**
  - **Kevin McGouldrick, University of Colorado**
  - Giada Arney, GSFC
  - Dave Atkinson, JPL
  - Dave Crisp, JPL
  - Mona Delitsky, CSE
  - Sebastien Lebonnois, LMD, Paris, France
  - Sanjay Limaye, University of Wisconsin
  - Kandis-Lea Jessup, SWRI
  - Paul Steffes, Geogia Tech

- **Surface and Interior Science**
  - **Bob Grimm, SWRI, Boulder**
  - **Lori Glaze, GSFC**
  - Attila Komjathy, JPL
  - Siddharth Krishnamoorthy, JPL
  - Alan Treiman, LPI
  - Gerald Schubert, UCLA
  - Tommy Thompson, JPL

- Experimental techniques identified and evaluated
- Instruments with multiple science functions e.g. magnetometers identified
- Contributions to VEXAG Goals Objectives and Investigations (GOI) assessed

Scientific Assessment of Aerial Platforms

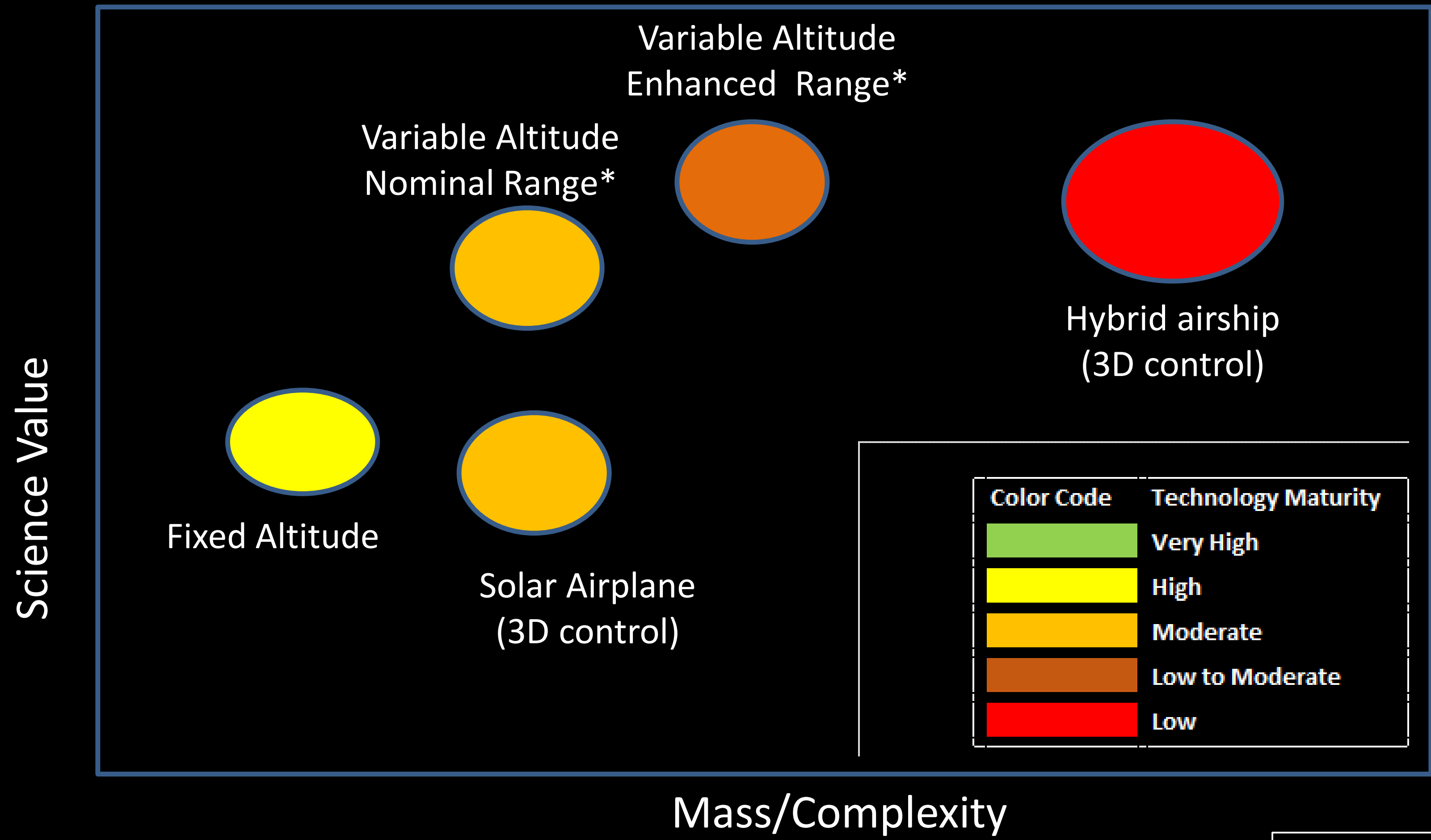
VEXAG Goals, Objectives and Investigations				Venus Aerial Platform and Sonde Types with Altitude Range (km)							
Goals	Objectives	Investigations	GOI Code	Constant Altitude	Variable Altitude Aerobot		3D control		Probes/Sondes		
				SP Balloon	Nominal Range	Enhanced Range	Solar Airplane	Airship VAMP	Large Probe	Targeted Sonde	Shallow Sond (mult)
				55	50 to 60	40 to 60	66 to 75	50 to 60	65 to 0	55 to 0	60 to 40
Atmosphere	Atmospheric Evolution	Solar Nebula/noble gases	I.A.1								
		Atmospheric Escape	I.A.2								
	Radiative balance, climate and superotation	Global circulation	I.B.1								
		Radiative Balance	I.B.2								
		Vertical motions	I.B.3								
	Clouds and Haze characterization	Cloud chemistry	I.C.1								
		Greenhouse /Cloud physics	I.C.2								
		Role of lightning	I.C.3								
		Biologically relevant chemistry	I.C.4								
Surface and Interior	Geodynamics	Stratigraphy/deformation	II.A.1								
		Radiogenic He_4 Ar_{40} in atmos	II.A.2								
		Geophysical studies	II.A.3								
		Active volcanism and tectonism	II.A.4								
		Absolute rock ages	II.A.5								
	Differentiation	Elemental composition	II.B.1.								
		Large scale composition variations	II.B.2								
		Structure of crust	II.B.3								
		Core and mantle structure	II.B.4								
		Radiogenic crustal elements	II.B.5								
		Subsurface layering	II.B.6								
Interior Surface Atmosphere	Liquid water and the greenhouse effect	History of water from Isotopes	III.A.1								
		Role of water in tessera	III.A.2								
		Hydrous minerals and sediments	III.A.3								
	Interactions of interior-surface and atmosphere over time	Elemental composition-noble gas	III.B.1								
		Rock weathering investigations	III.B.2								
		Altitude profiles of reactive species	III.B.3								
		Sulfur outgassing from surface	III.B.4								
	Other	Solid Body Atmosphere Ang Mom	NA								

Necessary and sufficient to address the investigation in the GOI

Necessary but not sufficient

Complementary to a primary measurement

Venus Aerial Platforms – Design Sweet Spot



Altitude controlled balloons represent a "sweet spot" in the aerial platform option space.

* Nominal Range
Altitude 50 to 60 km

* Enhanced Range
Altitude 40 to 60 km

Key Findings

- Aerial Platform Development
- Modeling and Simulation
- Science and Instrument Development
- Earth Based Flights for Engineering and Science
- Synergies with CubeSats and SmallSats

Key Findings- Aerial Platform Development

- Superpressure (Fixed Altitude) are the most mature of the balloons options but still require investment to reach TRL 6 when they would be ready for targeted science missions today. Scaling to larger sizes will require further work.

- Variable Altitude balloons have the potential for a substantial enhancement of the science over fixed altitude balloons without a commensurate increase in size and complexity of the platform, but will require some new technology.
  - A competitive technology program funding several different concepts would be an effective way to determine the most promising approaches
  - The program should include designing and building subscale prototypes followed by laboratory and flight tests.
  - Following an independent evaluation of the different options a full-scale prototype of the selected option should be built.

- Solar powered airplanes and hybrid vehicles show less promise for application to a mission during the next Planetary Science Decadal Survey
  - Two SBIR funded tasks may help clarify whether solar airplanes have promise
  - The aeroentry challenges is the main impediment to hybrid vehicles

Key Findings- Modeling and Simulation

- Venus Environment Models
  - Incorporate key parameters affecting aerial platform including the velocity fields, the cloud structure, and the solar and thermal radiation fluxes
  - Integrate data from recent orbital missions Venus Express and Akatsuki
  - Build on existing capabilities with much of the expertise now residing in Europe and Japan

- Aerial Platform Models
  - Describe the behavior of different fixed and variable aerial platform concepts in the Venus environment.
  - Should be accessible to the developers of these aerial platform concepts so they can be used in evaluating and comparing those concepts
  - Need validation of model predictions with Earth flights of Venus aerial platform prototypes

Key Findings- Earth-Based Flight Tests for Engineering and Science

- Aerial platform flight tests and experiments should be implemented not only for engineering purposes but also to demonstrate and develop scientific techniques.

- Some research programs are already underway focused on developing new geophysical techniques – EM sounding and infrasound seismology but it would be desirable to extend this to atmospheric investigations

- A dedicated test bed program would be an effective way to validate the performance of instruments in operational environments, as well as to train scientists and engineers in the unique challenges of aerial platform missions.

Key Findings- Science and Instruments

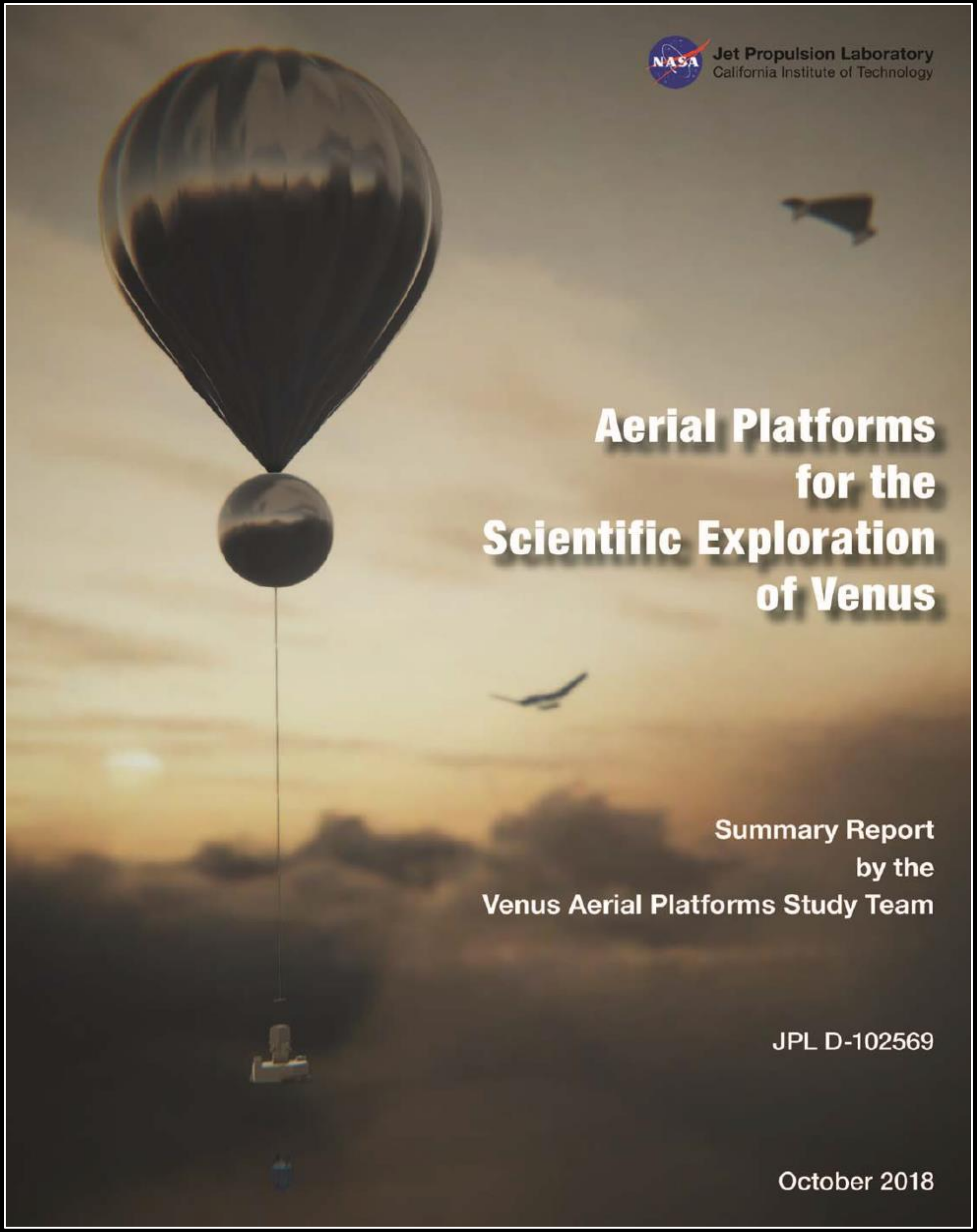
- Aerial platforms enable scientific investigations addressing all three major goals established by VEXAG:
  - Atmosphere,
  - Surface and Interior
  - Surface-Interior-Atmosphere Interaction.
- Development of new experimental techniques and miniaturization of existing ones are needed in order that aerial platform missions can deploy rich and diversified scientific payloads and fully exploit the promise of aerial exploration of Venus.
- NASA's PICASSO and MATISSE technology development programs provide opportunities for advancing these capabilities

Key Findings- Synergies with SmallSats-CubeSats

- Miniaturized spacecraft systems are needed for aerial platforms because of mass and power constraints to exploit science potential
  - relay and direct-to-Earth communications,
  - guidance navigation and control
  - Solar power
  - autonomous operations

- There are important synergies with the technology needs of interplanetary SmallSats and CubeSats. Radiation issues are mitigated for Venus aerial platforms because of atmospheric shielding

- SmallSats and CubeSats are also a cost-effective way of conducting synergistic science at Venus and providing relay communications, continuous tracking and attitude determination to the aerial platform.



Pre-Decisional Information -- For Planning and Discussion Purposes Only

Summary

- Venus Aerial Platforms (VAPs) could offer a credible pathway to long duration in situ missions at Venus. Missions which explore the temperate zone in the Venus clouds are the place to start

- Focusing on the temperate zone enable us to capitalize on the rich heritage of conventional sensors and electronic systems.

- Although the VAP technology for the SP platform is almost ready now, a multi-year investment program focusing on variable altitude capability would enhance the science capability of these platforms

- Among the opportunities for the application of VAP technology are:
  - Joint NASA Russian Venera D Mission Concept– NASA contribution
  - Venus Flagship Mission – currently being studied by NASA
  - Venus Bridge – atmospheric elements
  - Future competitive opportunities – New Frontiers and Discovery